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High-rise buildings and environmental factors

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A B S T R A C T

Today, energy has a key role in socio-economical development of a country. By exhausting fossil fuels as one of the largest energy consumption sources throughout the world, it seems to be vital to find renewable alternative energy sources or ways of reducing energy demands, especially in tall buildings with their great potential to use sustainable sources because of their height. In this study, the main problem is that the construction builders and users do not know the excessive energy saving potential of high-rise buildings. So, as a priority, this matter should be more concentrated on while designing by architects. These days, in my own country Iran, due to population growth and industrial development, the amount of energy consumption is increasing. This can show the importance of the problem. So, the Tehran International Tower, which is the highest residential tower in Iran, was chosen as a case study. Thus, the overall objective of this study is making tall building architects more aware of the neglected sustainable potential ways to diminish energy consumption. Meanwhile, this study tries to illustrate the effects of some environmental factors, such as air pressure and density, wind speed and other similar factors in high-rise buildings, from architects and ordinary people's points of view and comparing these attitudes with each other in the case study. Finally, as buildings use a huge amount of generated energy in the world, and high-rise buildings are an inevitable part of the community, they can meaningfully contribute in reducing energy consumption by using renewable energies and new ideas in designing. Moreover, the result of this research shows that sustainable skyscrapers can be energy efficient and are closely related to their site and environment.

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1. Introduction

Living without using energy is really far beyond reality, especially in today's modern societies. Energy is significantly used nowadays and one of the concerns of governments and the public is the global warming phenomenon and decreasing carbon dioxide content of the atmosphere [1] and increasing energy usage which damages the environment as well [2]. On the other hand, when population grows the demand for buildings as shelters increases, which in turn leads societies to choose high rise buildings as a solution [3]. So, regarding the environmental issues these structures should be '*environment friendly*' and substitute fossil fuels with renewable energies. But, unfortunately, the first built skyscrapers neglected this vital issue and considered their functional efficiency instead [4]. So, in order to achieve more energy efficient constructions a new balance needs to be applied between these two factors, which are also motivated by both economic and environmental concerns.

Iran is one of the largest countries in the southwestern part of Asia, and Tehran is its capital city with approximately 8.5 million inhabitants in 2011 [5]. This metropolis is plagued by severe air pollution. So, each effort toward reducing this problem will be vital. Thus, the Tehran International Tower was selected as a case study, which is located in a 35,000 square meters site.[1] Being more accurate, it is situated in the Amirabad neighborhood in the northern part of Tehran, which is one of Tehran's 22 districts.

One of the fundamental challenges over the past decade has been acquiring more renewable energies to substitute fossil fuels. Therefore, all the common practices have been intensified and efforts done to utilize the earth and near-grade environment as a source of energy [6]. Apart from wind and solar energies, architects do not usually consider the sky as a source of additional benefits and only a few studies have been done on the effect of height on high-rise buildings' energy consumption. So, what the sky can offer and its impacts on the environment should be a question, which in turn can be considered as a problem to better understand the effects of the environmental factors, which vary with altitude and have a consequent effect on the annual total buildings cooling and heating energies. In other words, the problem is that skyscraper architects and constructors have not paid attention to the great potential of their buildings via their vast facades.

Considering the above data, this paper emphasizes on finding out the effect of the main environmental factors, which can be considered as a way of reducing building energy demand instead of seeking for substitute energy sources. Therefore, specifically, the effects of these environmental factors on high-rise buildings, the way these factors would change with altitude and their impacts on the annual total buildings cooling and heating energies would be considered as questions. Thus, the main objective of this paper is to make high-rise building designers and builders more aware of the extra sources of sustainable energies in the sky.

2. The high-rise buildings and skyscrapers

These days, "Buildings are the main destination for the nation's power supplies and hence the main sources of carbon dioxide emissions" [7] and high-rise structures are an inevitable part of our society building forms. Furthermore, skyscrapers are becoming more necessary, according to the effective use that they make of the available limited land [8]. Ecological design and sustainability of tall buildings are in fact more crucial than those of ordinary buildings. Constructing these buildings are inevitable, because of their scale and their huge amount of energy and material usage [8,9]. Therefore, tall buildings have a great potential for maintaining and recycling resources. Moreover, high-rise building design is complicated and requires more experience [10]. So, for many reasons, the sustainable design of skyscrapers needs to be addressed.

Some advantages of tall buildings are as follows:

- Material saving because of repetitive type plans.
- Observing standards and efficient contractors, especially in large quantities, lead to lower costs.
- More potential to reduce energy and material waste by using sustainable materials in elevations.
- Tall buildings occupy less land.
- Better use of daylight and thermal mass.
- Prepare better horizontal access for its inhabitants [11].

3. Sustainability

Sustainable architecture

People always consider the terms '*ecological building*', '*energy-efficient structure*', '*bioclimatic architecture*' and so on, instead of sustainable architecture, but these are just part of it, and sustainability in architecture is something more complicated. Thus, there are some kinds of buildings, which contribute the principle of a careful deal with natural sources with no functions [12]. In other words, sustainable buildings are "causing as little environmental interference as possible, such as, the use of friendly environmental materials that do not constitute a health hazard, low energy requirements, renewable energy use, high-quality and longevity as a guideline for construction, and last but not least, an economical operation" [13].

As shown in Fig. 1, it consists of three parts; economy, ecology and society [14]. Economical and ecological attentions are intensifying questioning the principle of effectiveness, because this fundament adopts an idea that our environmental sources are unlimited. However, the society largely depends on non-renewable sources.

Hegger et al. argued that, "with sustainable construction, apart from anything else, the architects' self-image is on trial" (p. 21). There are a number of ways and methods to assess buildings sustainability and also several different criteria for it, but this research concentrates on renewable energy potentials, especially in high-rise buildings as a part of sustainable architecture.

3.1. Sustainable building services

In essence, there are three essential aspects of sustainable building services: first, designers should pay more attention to the ecological consequences of the technical systems. Furthermore, it is a key factor for achieving extensive renewable energy

[1] The A.S.P Corporation management, personal communication, March 4, 2012.

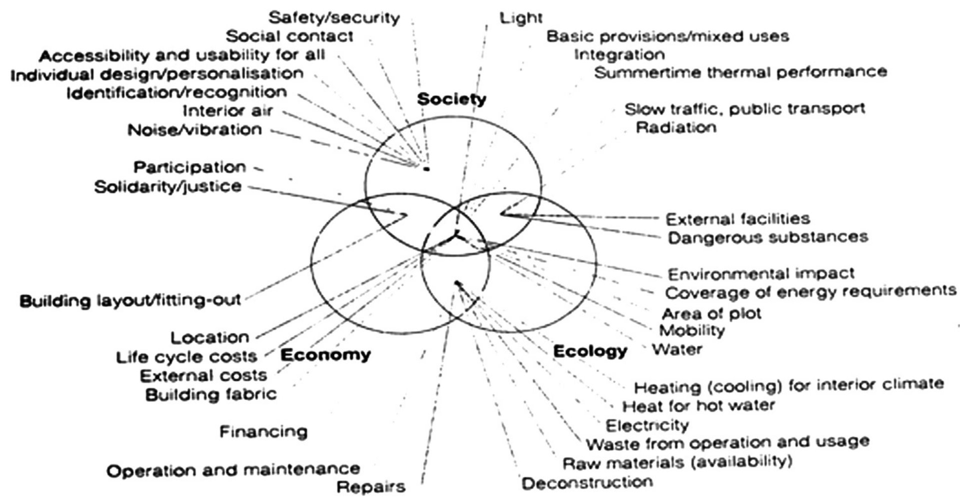

Fig. 1. Three parts of sustainability.
Source: Hegger et al. 2008:192

resources for building energy usage to guarantee a high energy performance. Second, to arrange the optimum solution for the particular project requirement, it is essential to provide a technical concept in the design. Finally, another key factor is the careful planning for both production and the cost of operation [15].

3.2. Natural resources

One of the most essential targets of sustainable buildings is to use as many natural resources as possible; somehow this heavily depends on climate [16,17]. On the other hand, apart from energy usage, to have low energy requirements, the local and prevailing climatic conditions should be considered as a key factor. Generally, the following rules can be considered as some initial principals of using natural resources [18,19]:

1. For higher thermal requirements, higher heat and solar insulation are needed [20].
2. Using the benefits of the passive solar system [21,22].
3. Utilizing the building structure as thermal storage.
4. Utilizing natural ventilation capability [23].

3.3. Renewable energies

Because of the fossil fuel limitations, we have to develop a new mechanism to substitute these sources of energies with renewable energies, which are dramatically based on environment and climate. Thus, although, assessing 100% renewable energy sources is extremely complicated task, by implementing them as a source of power, buildings could be '*environment friendly*' and attain '*zero emission*' [24]. So, the most important issue for the sustainable development of countries is the environmental protection [25]. According to that, "Renewable energy sources promise environmentally compatible energy usage. So, when using energy supplies exclusively from renewable sources we can conclude that the energy consumption is no longer relevant" [14]. However, the use of these sources are tied to the high cost, but fortunately, these days, progresses in renewable energy technology and storage devices have been made.

4. Research methodology

This research is based on two main phases, quantitative and qualitative. The first phase includes a survey in the prioritization of different sustainable criteria from the experts' point of view. Therefore, the researcher tries to achieve the purpose of this study by using '*observation*', '*interview*', and '*questionnaire*'. In the second phase, a survey has been conducted in order to identify the exterior environmental factors and their relationship with altitude that the designers would prefer to know, while designing high-rise buildings. So, according to this method, for data evaluation and computation the 'energyplus' and 'windographer' softwares are used.

4.1. Data collection methodology and discussion

In this part, all data were collected in two different periods; nine days in Tehran (April 2012), which was based on an overt method observation by photographing and surveying the Tehran International Tower as a field study, just for showing some characteristics of Iranian energy efficiency and usage in new high-rise building's development. From 557 units, 60 unit habitant were questioned (about 10% of all), that were both men and women between the ages 15 and 65 in order to understand user satisfaction as a result of a qualitative study by the researcher. Twelve close ended questions have been put in this structured questionnaire, which are five types in such a way that each of them helps the author to get to a specific goal. In other words, first, general information such as age, gender and block locations was asked. Second, whether they live there permanently or temporarily and the length of the time they had lived there. Third, the knowledge and ideas of inhabitants about environmental factors were evaluated. Fourth, the level of habitant satisfaction was assessed. Finally, the last question deals with the energy efficiency method. Furthermore, I have to mention here that the aim of this questionnaire is to understand and specify the amount of residents satisfaction of the first attempt for a sustainable residential skyscraper in Iran.

Meanwhile, interviews—open ended questions—with two groups had been done to find out the level of expert's knowledge about opportunities of height, its probable problems and what is done in that case in Iran high-rise buildings. First, with 15 architecture master students—men and women—between 25 and 30 years in Tehran and secondly with 15 Iranian architecture master students in Eastern Mediterranean University (EMU)

Fig. 2. East Facade of the Tehran International Tower.
Source: Author, 2012.

Fig. 3. South Facade of the Tehran International Tower.
Source: Author, 2012.

Fig. 4. South Facade Huge vertical double glazing windows inside view.
Source: Author, 2012.

located in Famagusta, North Cyprus during three days (March 2012) to understand the ideas of the new generation of architects living in the country and abroad about the subject. It should be mentioned that six designers and technicians in the construction office were interviewed as experts to assess their professional point of view. This might lead us to an interactive relation between the architects' opinion about using renewable energies in high-rise buildings as a part of design and what is happening in reality. Finally, in order to analyze statistic's data as a result of the quantitative study, documentary research, which consists of library references and gathering information from Tehran municipality and Iranian Energy

Fig. 5. Using an egg crate shading devices in order to benefit both vertical and horizontal planes in all directions.
Source: Author, 2012.

Organization as an association, which is responsible for utilizing energy usage in the country was done.

As described in the research methodology and data collection, this paper collects data in three categories including '*observation*', '*questionnaire*' and '*interview*'. The Tehran International Tower—as a case study—is situated in a 35,000 m^2 site, bound to the north by Sheikh Bahai Expressway, to the south By Hakim Expressway, to the east by Kordestan Expressway and to the west by Chamran Expressway, all of which facilitate access to various parts of the city.

4.1.1. Observation

The Tehran International Tower is the first skyscraper in Iran, which has somehow attempted to consider the environmental effects and sustainability according to new municipally rules. It was constructed in 2007. The infrastructure of the tower is 220,000 m^2, and it is the highest residential complex in the country up to 2012 with the height of approximately 164 m. This skyscraper has three wings and 56 stories (Figs. 2 and 3). Furthermore, the tower structures consist of three main reinforced concrete load-bearing wall's core along the three wing angle of 120° from each other. And ceilings as well as walls have been constructed with concrete slabs. Moreover, internal walls are a combination of concrete and dry walls with using sound and thermal insulation for optimization of energy usage. Hence, for designing cute and rocky facade in this tower, designers considering factors such as air pressure and solar radiations and also project progress velocity use prefabricated concrete (GFRC) with simple patterns and also huge windows—1.4 m × 3 m—with the same typology among them in each facade.[2]

Daylighting is the technique of optimizing the use of openings and some kinds of reflective surfaces in order to gain effective internal day light [26]. In this project in order to reduce artificial lighting, saving energy in cooling and heating parts and also maximizing visual comfort, the designers use huge vertical double glazing windows (Fig. 4). These 1.4 m × 3 m windows are located at the distance of 0.5 m from each other in every facade with the same typology.

Shading devices and well-designed sun controllers dramatically decrease the heating gained through the solar radiations, especially in a hot dry (arid) climate such as Tehran. So, it reduces the energy consumptions for cooling purposes and also has a significant effect on daylighting quality. Generally, the shading devices reduce indoor temperature. In this high-rise building, each window is inscribed by rigid 1.4 m × 3 m overhang shading devices with reveal depth of 1.2 m (Fig. 5). Therefore, by using combined (egg crate) shading devices, this building can benefit

[2] The A.S.P Corporation technical management, personal communication, April 3, 2012.

Table 1
The EnergyPlus Software input data samples for the Tehran International Tower.
Source: Author, 2013.

Quantity	Note	Description
Latitude	35°42′22″ N	The geographical (north/south) coordinates of the test building
Longitude	51°25′38″ E	The geographical (east/west) coordinates of the test building
Surface azimuth	257°	Direction surface faces (east: +90º; West: 270° or −90°)
Surface elevation	0°	Elevation of surface (vertical: 0°; horizontal: 90°)
Day number	92	1, 2, 3, ..., 365
Solar time	Computed	Function of time and longitude, day number and time zone
Solar hour angle	Computed	Function of solar time

Fig. 6. The Tehran International Tower site plan.
Source: the A.S.P Corporation, 2012.

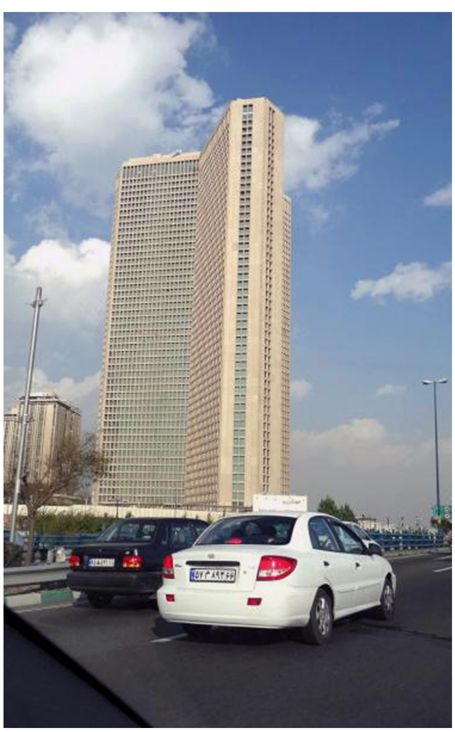

Fig. 7. West view of the Tehran International Tower.
Source: Author, 2012.

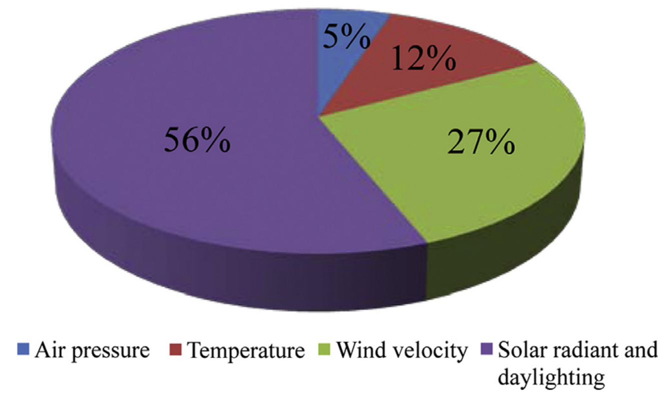

Chart 1. Residents opinion about sufficient environmental factors, which are reducing usage in high-rise buildings energy.

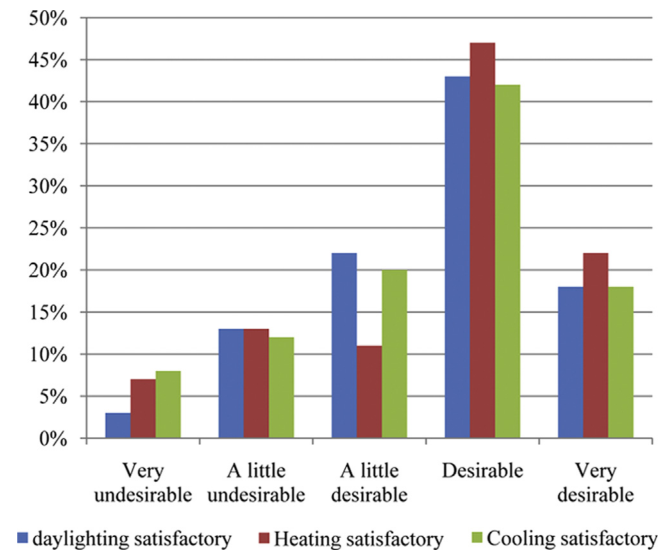

Chart 2. Residents use of renewable energies satisfactory.

from both vertical and horizontal planes in all directions, which leads to saving a significant amount of energy used in cooling and heating sector. Although these controllers somehow prevent daylighting, the huge window size reduces this negative effect and also improves user visual comfort by controlling glare and reducing contrast ratios. In addition, these shading devices have an intensive impact on the building appearance and form the facade of the tower and also divide its surface to provide human scale.

In order to compute the effects of the above factors—orientation, daylighting and shading devices—the EnergyPlus software, by using Table 1 information, which mostly exist in the EPW file and the rest that their amounts are noted below must be considered as manual input. Accordingly, it should be mentioned that in order to use 'EnergyPlus' software the input data should be in TMY or TMY2 format, which are available in the EPW files. The Typical Meteorological Year format data (TMY) are three-month-long data files, which are used in the original field trials of the test procedure; the TMY2 format data are year-long data files that may be more convenient for users and are here used for case study analysis. However, in this research, the input weather data, which is used for the software analysis and simulation is a text-based format retrieved from the TMY2 weather format. Likewise, in order to attain common format output, the 'Open Studio Results Viewer' is used. It reads the output of 'EnergyPlus' and displays the data in the form of line plots and also two dimensional flood plots.

Eventually, analyzing TMY2 format data plus (Table 1) information shows that by considering the orientation, adequate amount of opening to benefit from natural daylighting and using sufficient shading devices, the Tehran International Tower total energy consumption at its top, decreases as much as about one-third of an ordinary high-rise building in that district.

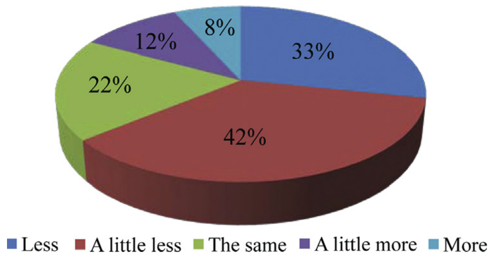

Chart 3. Residents opinion about bill payments in comparison with ordinary buildings.

Solar and wind energies: As this skyscraper is composed of three wings angle of 120° from each other, it can benefit from all solar radiations and winds in all directions (Figs. 6 and 7). Although the south direction is the best for building orientation in Tehran and the dominant wind blows from west to east and vice versa and predominant wind blows from north-west to south-east and vice versa [27], for such a tall and huge residential project like the Tehran International Tower, this form is one of the best options. Moreover, although some energy efficient aspects of the project were omitted during the construction level just because of some economical problems, the technical office of the project claims that it can save 7–15% energy in ventilation segment.[3]

4.1.2. *Questionnaire*

To find out people's opinion and to understand how much these sustainable techniques have affected the inhabitants' lives, the questionnaires were filled out. To evaluate, a field study questionnaire for 60 residents—as described in the data collection's part—was carried out. After collecting and analyzing them, it was understood that although the Tehran International Tower residents (about 83%) do not know much about sustainable potentials of height except solar energy and wind power (Chart 1), they are approximately satisfied (73%) with living in the tower, which has been built sustainable (Chart 2). In other words, about 73% of residents have believed that the sustainable consideration of the tower makes desirable or very desirable effects of total annual building energy demands.

To approve the residents' claim about their satisfactions, they were asked about the hours they benefited natural light and used mechanical ventilation systems whether for cooling or heating purposes. In brief, 61% of habitants are evaluating the apartment's natural lighting satisfiable. This amount is at the highest point of reducing heating system usage, which is approximately 69% and also it is about 59% for applying cooling system. Therefore, in general, about three-fourth of inhabitants support the idea of usefulness of using renewable energies in high-rises by admitting that they paid less or at least a little less in comparison to ordinary buildings (Chart 3).

4.1.3. *Interview*

The majority of experts interviewed believed that the rapid growth of energy consumption and great need for energy in one hand, and limitations of unsustainable fossil energy sources and also environmental issues resulted from the consumption of the mentioned energies in the other hand, make the use of renewable energies vital and reminds us the necessity of using such modern energies in human societies and high-rise buildings as one of the biggest human shelters too. But unfortunately, considering the low price of fossil fuels in Iran and also learning the culture of consumerism and commercialism as well as inattention to lack of sustainability of current energy sources in Iran, the country's per capita consumption is multiplied in comparison with global variables and there were not enough attempt in sustainable housing especially in the part, related to benefits of height, whereas such behavior is not rooted in Iranian national culture.

[3] The A.S.P Corporation technical management, personal communication, April 3, 2012.

Fig. 8. Wind catcher, Taft, Iran [29].

According to the above issues, although the importance of sustainable design and energy efficiency is apparent, it seems that the majority of architects still have limited interest in energy. Accordingly, aside wind and solar powers, they do not generally look towards the environmental factors as the sources of additional advantages and just little study has been done on the effect of height on the energy consumption of towers. Thus, in countries like Iran with great potential of renewable energy sources, the effects of environmental factors such as temperature and air pressure are not commonly considered. Though, the Tehran International Tower is not a very sustainable skyscraper, but as an initial attempt for sustainable development, it is respectful. Certainly, the results of such structures lead to some changes in the architecture of buildings so that they will be more compatible with their surroundings and also reduce energy consumption in the near future.

5. Investigations of sky-sourced sustainability

While there are so many possible solutions to benefit altitude in high-rise buildings, this research just covers some of these suggestions such as temperature, air pressure, air density, wind power, solar energy and the way we can promote them.

5.1. *Temperature*

Tehran's climate is hot and arid in summers and cold in winters [27]. Thus, its high-rise buildings can benefit from dry bulb temperature decline as they rise in height. It is not a new idea to take advantage of the lower temperatures above ground; it has been used in the old traditional Iranian wind catcher systems (Fig. 8). Leung (no date) stated that, “In standard atmosphere, dry bulb temperature decreases linearly with elevation in the troposphere (lapse rate in a lower atmosphere)” [28].

To calculate lapse rate, we can use three different ways; American Society of Heating, Refrigerating and Air Conditioning Engineers method (ASHRAE), Dry Adiabatic Lapse Rate (DALR) and Saturated Adiabatic Laps Rate (SALR). The ASHRAE method is suitable for an ‘*average*’ climate such as Tehran. According to the above information, Tehran's skyscrapers can profit from dry bulb temperature decrease as they arise with height. Thus, the Dry Adiabatic Lapse Rate (DALR) method is used in order to analyze

Table 2
The Tehran International Tower average temperature variation with altitude.
Source: Author, 2013.

Altitude (m)	0	50	100	150	200	250	300
Temperature (°C)	27.8	27.53	27.1	26.71	26.64	26.08	25.65

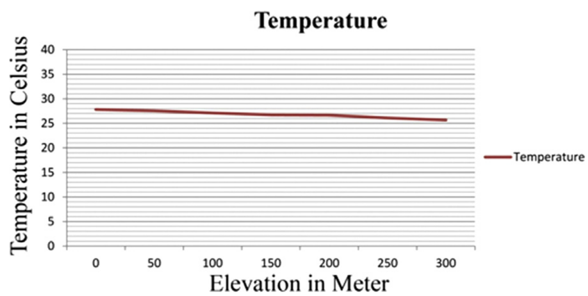

Chart 4. The Tehran International Tower Exterior Temperature Gradient in Summer. *Source*: Author, 2013.

data. So, in this research, all the following calculations were done in accordance with this method considering Tehran's altitude, latitude and climatic information and the results are illustrated in the charts.

The amount of temperature decreases according to altitude, for a parcel of dry or unsaturated air, rising under adiabatic conditions is known as DALR. The term 'adiabatic' means that no heat transfer occurs into or out of the parcel. As the bodies of air involved are very large and air has low thermal conductivity, heat transfer through conduction is very slight.

Air expands while ascending because of lower air pressure at higher altitudes, and while expanding it pushes the surrounding air due to a process called thermodynamics [30]. Since this air gains no heat but does work, it loses its internal energy and in result its temperature decreases [31].

Since for adiabatic process

$$PdV = -VdP/\gamma$$

The first law of thermodynamics can be written as

$$nc_v dT - VdP/\gamma = 0$$

Also since $\alpha = V/n$ and $\gamma = C_p/C_v$ we can show that

$$C_p dT - \alpha dP = 0$$

where C_p is the specific heat at constant pressure and α is the specific volume.

Assuming an atmosphere in hydrostatic equilibrium [32]

$$dP = -\rho g dz$$

where g is the standard gravity and ρ is the density. Combining these two equations to eliminate the pressure, one arrives at the result for the DALR [33]

$$\Gamma_d = -dT/dz = g/C_p$$

where T is temperature and z is altitude.

It should be noted that in some cases, Γ or α can be used to represent the adiabatic lapse rate in order to avoid confusion with other terms symbolized by γ [31].

Lapse rate always occurs in the lower atmosphere, but sometimes temperature inverses and when the lapse rate applies for cooling equipment sizing, close care must be taken. And this lapse rate can help in energy consumption criteria through the whole

Table 3
The Tehran International Tower Site and weather summary—TMY2 format.
Source: Drawn by Author, 2013.

Weather type	Lapse rate	Latitude	Longitude (local site)	Sea level altitude	Site altitude	Ground reflectivity	Site
Temperate	8 °C/km	35°42′22″ N	51°25′38″ E	1200 m	1300 m	0.2	Flat, unobstructed
Dew point temperature (constant)	Temperature	Humidity ratio	Mean annual wind speed	Maximum annual wind speed	Global horizontal solar radiation annual total	Direct normal solar radiation annual total	Diffuse horizontal solar radiation annual total
15.0 °C	27 °C	(0.010 lb moisture/lb dry air)	2 m/s	8.9 m/s	6453 MJ/m² (568 kBtu/ft²)	5418 MJ/m² (477 kBtu/ft²)	2914 MJ/m² (257 kBtu/ft²)

Table 4
Constant parameters of the Barometric formula.
Source: Drawn by Author, 2013.

Parameter	Description	Value
P0	Sea level standard atmospheric pressure	101,325 Pa
L	Temperature lapse rate,$=g/c_p$ for dry air	0.0065 k/m
C_p	Constant pressure specific heat	1007 J
T_0	Sea level standard temperature	288.15 K
g	Earth-surface gravitational acceleration	9.80665 m/s^2
M	Molar mass of dry air	0.0289644 kg/mol
R	Universal gas constant	8.31447 J/(mol K)

year. By using the average summer temperature—from July to September—, and Tehran (Mehrabad) Meteorologic Organization's Statistics, numbering the above formula in height of 160 m for Tehran is done and it is approved that $\Gamma = 8\ ^\circ$C/km as shown in Table 2.

To better understand the effect of dry bulb temperature with height, the above information can be illustrated in Chart 4.

As it is obvious, in standard atmosphere, dry bulb temperature almost linearly declines with elevation in the troposphere. In this case, at a ground level, based on the summer design, dry bulb is 27.8 °C; the temperature at the peak point of the skyscraper (160 m) is approximately 26.3 °C. In order to benefit from the EnergyPlus software the TMY2 information should be saved in an EPW file format[4] as a software input. The EPW (weather data format) is very flexible. In addition to the usual weather data (temperatures, solar radiation data), the format embodies other information from the location and weather data (for example; design conditions, calculated ground temperatures, typical and extreme weather periods). The main factors of this information are gathered at Table 3 as a sample.

Based on user's description of a building from the perspective of the building's physical make-up, associated mechanical systems, etc., EnergyPlus will calculate the heating and cooling loads necessary to maintain thermal control setpoints. Therefore, by assuming all factors with the same amount and just changing the site altitude and temperature, the difference between these amounts can show the energy saving potential of the skyscraper. Thus, in this specific case, by software data evaluation, it could be understood that by applying the effect of temperature drop in the height of 160 m, in a temperate climate about 2.4% of energy consumption could be saved.

5.2. Air pressure

Generally, the atmospheric pressure is calculated from the above equation, which is called the barometric formula [34]

$$P = p_0[1 - Lh/T_0]^{gM/RL}$$
$$\approx p_0[1 - gh/C_pT_0]^{cpM/R}$$
$$\approx p_0 \exp[-gMh/RT_0],$$

The constant parameters are as described in Table 4.

In the barometric formula, height (h) is considered as a variation factor. In this case, by numbering the formula, the atmospheric pressure can be calculated in a certain altitude. The results of these computations are shown in Table 5.

In order to comprehend the above information more deeply, they are illustrated as a graphical form in Chart 5.

[4] EPW files could be downloaded from the web site for EnergyPlus (http://www.energyplus.gov).

Table 5
Air pressure changes in the Tehran International Tower.
Source: Author, 2013.

Altitude (m)	0	50	100	150	200	250	300
Air pressure (Pa)	87.50	86.88	86.53	85.91	85.44	84.80	84.24

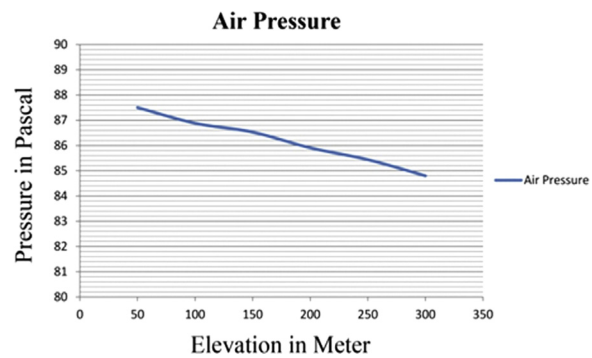

Chart 5. Air pressure changes in the Tehran International Tower.
Source: Author, 2013.

Table 6
Air density gradient in the Tehran International Tower.
Source: Author, 2013.

Altitude (m)	0	50	100	150	200	250	300
Air density (kg/m³)	101.30	100.83	100.42	99.81	99.11	98.64	98.25

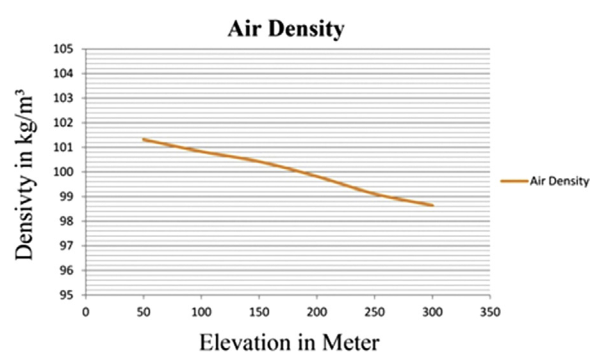

Chart 6. Air density gradient in the Tehran International Tower.. .
Source: Author, 2013.

Air pressure reduces with height. Outdoor pressure drop for the Tehran International Tower is demonstrated in Chart 5. Thus, as it is shown in the chart, the exterior pressure difference between the peak point and the bottom of the skyscraper is approximately 2.6%. Thus, although in the above computation the temperature factor is assumed as equable unite, the relation of pressure with sea level and air density, which is generally dropping off quicker at some latitudes with altitude, is implicit. So, calculating the effect of this item—atmospheric pressure—separately is not logical.

5.3. Air density

As it was mentioned, in this case, as the climate is considered as temperate dry air, the following equation can be used [35]:

$$\rho = P/RT = 8750000/287*300.95 = 101.30\ \text{kg/m}^3$$

Table 7
Windographer Software data input for the Tehran International Tower.
Source: Author, 2013.

Data set properties						
Latitude	Longitude	Elevation	Start date	End date	Duration	Calm threshold
35°42′22″ N	51°25′38″ E	160 m	2013-06-01	2013-09-01	3 months	4 m/s
Environmental conditions						
Mean temperature			Mean pressure		Mean air density	
29.7 °C			87.5 Pa		101.30 kg/m³	

In the above formula the air density at the ground level of the Tehran International Tower was calculated. Its density on the other height was calculated by the same method and the results are shown in Table 6. It should be just mentioned that in the formula (R) is a constant parameter and the amount of air pressure and temperature is retrieved from Tables 2 and 5.

To better understand the quantitative amount of Table 6, this information is drawn as a subsequent chart (Chart 6).

As described, air pressure declines with height; this leads to the expansion of outdoor air making it less dense. Therefore, air density decreases with altitude. This air density decrease is indicated in Chart 6. It can be understood from this chart that air density difference between the top and bottom of the tower is about 1.9%. Cooling thinner outdoor air through the ventilation system or even infiltration requires less energy. This is generally true since the outdoor air has a lower temperature. So, according to the energy simulation program, air density alone contributes to about 1.5% of energy savings for ventilation in the case study.

5.4. *Wind power*

Wind has some negative and positive effects. For structural engineers, it always causes trouble with height, but, on the other hand, we can use its benefits. According to Sartipipour (2011), Iran is located in a windy region with an average wind speed of 6 m/s [36]. Several factors depend upon the power of wind such as topological conditions of the site. Accordingly, in order to benefit from the Windographer software two types of data are necessary. These types of information can be categorized as '*Data Set Properties*' and '*Environmental Conditions*' (Table 7).

Then by using the above data as a software input, one of the Windographer outputs is a graph, which is illustrated as Chart 7.

In the case of analyzing the software data output, the wind speed in the certain altitude, which were used as a checkpoint in previous sections, can be retrieved from the above chart and the result is reflected in Table 8.

Eventually, by assuming all factors in Table 3 as constant parameters and just changing mean wind speed from 2 m/s to 8.9 m/s (retrieved from Table 8), the difference of these amounts can display the energy saving potential of the skyscraper. Therefore, in this specific case, by software data evaluation (EnergyPlus), it could be understood that by applying the effect of wind as an environmental factor in the height of 160 m, in Tehran temperate climate, about 3.9% of energy consumption could be saved. Furthermore, in high-rise buildings by aligning the fan intake with the prevailing wind, ventilation system can benefit from the exponential increases of wind speed and from a wind-assisted system [37,38]. Also, an increase in wind velocity could be beneficial to power generations and turbines, which are using wind energy.

5.5. *Solar energy*

Iran is among the top countries receiving solar radiations by having approximately 300 sunny days per year [36]. Using

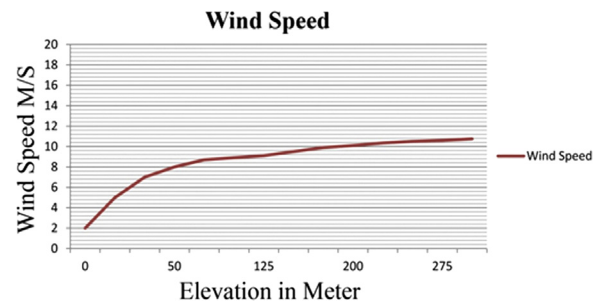

Chart 7. Wind speed changes in the Tehran International Tower.
Source: Author, 2013.

Table 8
Wind speed changes in the Tehran International Tower ().
Source: Author, 2013

Altitude (m)	0	50	100	150	200	250	300
Wind speed (m/s)	2	8	8.9	9.5	10.1	10.5	10.73

photovoltaic systems and solar collectors is suggested and has economic justifications in the region, which gains more than 3.5 kW h/m^2 solar radiation. Therefore, Tehran with a daily amount of a possibility of exploiting solar energy between 5.25 and 5.5 kW h/m^2 has a very good potential in this case [39].

The effects of solar radiation on vertical surfaces are a little complicated because it is composed of three different elements:

1. Direct normal irradiance, which is a function of apparent solar irradiation, solar altitude, and the aerosol/water vapor in the air.
2. Diffuse radiation from the sky, which is impacted by additional angle of incidence of the sun and the ratio between diffuse radiations falling on a horizontal surface under a cloudless sky over direct normal irradiation on the earth's surface on a clear day.
3. Diffuse radiation from the ground depends on all the above mentioned factors plus ground reflectivity and the surface angles.

Therefore, for high-rise buildings, although the direct normal irradiance and diffuse radiation are increasing, the diffuse radiation from the ground is reduced because of a thicker air mass to travel through. Consequently

> "Under direct-beam clear-sky situations, the amount of solar radiations in general increases with altitude. This is especially true for UV radiation above the friction zone. For each 152.5 m (500 feet) increase in altitude, there is roughly a 2–2.5% increase in incident UV radiation" [40].

Eventually, for calculating the entire building energy simulation model, all the above methods should be considered once again. In previous calculations, except for one of the variations the rest

Table 9
The Tehran International Tower surface constructions ().
Source: Author, 2013

Material	Conductivity (W/m K)	Thickness (m)	*U*-value (W/m² K)	*R*-value (m² K/W)	Density (kg/m³)
Walls					
GFRC	1.28	0.155	4.16	0.24	1714
Roof					
C5-concrete	1.73	0.1015	17.04	0.059	2243
Floor					
C5-concrete	1.73	0.1015	17.04	0.059	2243

were considered as a component in order to calculate the effect of each factor in the height of 160 m. For instance, in order to calculate the effect of air pressure in height, air pressure at the top of the tower was compared with its amount in ground level floor. However, this time, for computing the total impact of mentioned environmental factors all the previous data were considered as variation data input for the 'EnergyPlus'. In this case, by considering the EPW file, which includes climatical site information (Tables 1 and 3) and plus the following information (Table 9), obtained from previous data evaluated part, the entire building energy simulation can be started.

Therefore, by adding this information to the software, the difference of the energy usage in the ground floor and the height of 160 m can be evaluated. Then this difference can be considered as a saving energy consumption potential of the building. So, in brief, our simulation models illustrate that considering the building orientation, benefiting from proper daylighting and using shading devices, and also the effect of solar radiation, wind energy, air pressure and density at the peak point of the building, lead to save about 32% in the Tehran International Tower.

6. Conclusion

In today's world, which is affected by global warming and also by indefinite amount of energy supplies, it is very essential to find ways to save energy. Buildings consume a great portion of generated power in most countries, and high-rise buildings are an inevitable part of the modern societies. They can play an important role in reducing energy consumption by using renewable energies and new ideas in designing. Moreover, sustainable towers can be energy efficient and closely related to their site and environment.

Based on the data collected in the field study, from written documents, through overt method observation and softwares calculation results, it could be mentioned that although the Tehran International Tower does not strongly use renewable energies—just by considering some simple sustainable principals and environmental factors such as vertical double glazing windows for spreading out daylighting, shading devices, thermal insulation and proper orientation—it is estimated that it could reduce energy consumption to approximately 30–35% in the highest level in comparison with an ordinary building, which in this significant case as the first attempt to a sustainable tower in Iran could be respectful and admirable. Furthermore, using these sustainable principles not only decreases the amount of energy usage, but also improves the esthetic aspects of the project by privileging modern style identity to it.

Data was collected by structured questions and was analyzed by Microsoft Excel 2007. Results show that although most of the skyscraper residents (about 83%) do not know much about new sources of renewable energies in high-rise buildings (Chart 1), simultaneously, they are nearly highly satisfied (about 73%)[5] with natural sources of energies, which are used in their flats (Chart 2). In addition, about three-forth of the inhabitants believe that they pay less or at least a little less in comparison with ordinary buildings (Chart 3). Therefore, this questionnaire could prove data gathered by observation.

In addition, everyone knows that energy plays an important role in today's world and it has turned into a very crucial factor in the process of development. To optimize energy consumption, which is considered as one of the key factors for having access to a sustainable development throughout the world, construction team interviewers believed that one of the major problems of this tower is with its instruments, which prevented it from being constructed as it had been designed with the low cost of energy consumption in comparison with the high initial cost of constructing them. Also, it can be understood from comparing interviewees that both groups of Iranian architecture master students in the country and abroad were in agreement with experimented experts in this case, that as a designer, we need to know and do much about energy efficiency and renewable energies, especially, in high-rise buildings. Furthermore, it should be mentioned that the documentary research supports all data collected in this research as a result of percentages statistics and qualitative study, which was collected from library resources and some responsible organizations, which were mentioned before.

Consequently, this paper reviews some potential and available renewable energy sources, environmental factors—to be embedded in high-rise buildings—and investigation on the Tehran International Tower as a case study and illustrates that environmental factors can meaningfully contribute to the sustainability of tall buildings. For instance, in the current situation, it saves energy consumption at the highest point of the tower between 30% and 35%. But in ideal circumstances the amount of energy saving could be much more. Therefore, on the basis of data analyzed and by considering different methods, it seems that, although everybody appreciates using new sources of energy, ordinary people need more knowledge about these new sources of energies and experts need to pay more attention to it in their design. Finally, this issue needs more governmental investigation.

References

[1] Smith PF. Architecture in a climate of change: a guide to sustainable design. Oxford/Amsterdam/Boston/London/New York/Paris/San Francisco/Singapore/Sydney/Tokyo: Architectural Press; 1988.
[2] Hamzah TR, Yeang K. Bioclimatic skyscapers. London: Ellipsis London Press Ltd.; 2000.
[3] Tsui E. Evolutionary architecture: nature as a basis for design, Wiley. 1999.
[4] Thomas R. Environmental design: an introduction for architects and engineers. 3rd ed.. . London/New York: Taylor & Francis Group; 2006.
[5] Iransamaneh 2011, Tehran's population, Available online, ⟨http://www.tabnak.ir/fa/news/204754/⟩.
[6] Wines J. Green architecture. In: Keller C, Senger N, editors. Italy: Benedikt Taschen Verlag GmbH; 2000.
[7] Cox G, Girardet H, Pank W. Tall buildings and sustainability: report. London: Corporation of London; 2002.
[8] Yeang K. The green skyscraper: the basis for designing sustainable intensive buildings. Munich, Germany: Prestel Verlag; 1999.
[9] Fracastoro GV, Serraino M. A methodology for assessing the energy performance of a large scale building stock and possible applications. Energy Build 2010844–54(Elsevier).
[10] Scott A, editor. New York, USA: E & FN Spon; 1998.
[11] Yeang K. The skyscraper bioclimatically considered. In: Wiley J, editor. Chichester, UK: Wiley-Academy; 1996.
[12] Yeang K. Eco skyscrapers. In: Lucy B, editor. . Victoria, Australia: The Images Publishing Group Pty Ltd.; 2011.
[13] Bauer M, Mösle P, Schwarz M. Green building: guidebook for sustainable architecture. Heidelberg/Dordrecht/London/New York: Springer; 2010.

[5] Including 61% from daylighting, 69% from natural heating and 59% from natural cooling.

[14] Hegger M, Fuchs M, Stark T, Zeumer M. Energy manual: sustainable architecture. Basel/Boston/Berlin: Birkhäuser Verlag AG; 2008.
[15] Ke, M, Qi, L, Qi, Z. A preliminary study on renewable energy's using mode of Tibet residential buildings. In: Proceedings of the international conference on materials for renewable energy & environment ICMREE. China: IEEE Conference Publications; 2011. p. 2058–61 http://dx.doi.org/10.1109/ICMREE.2011.5930742.
[16] Akella A, Saini R, Sharma M. Social, economical and environmental impacts of renewable energy systems. Renew Energy 2009;34:390–6.
[17] Slessor C. Eco-Tech: sustainable architecture and high technology. UK: Thames and Hudson; 2001.
[18] Lior N. Sustainable energy development: the present (2009) situation and possible paths to the future. J Energy 2010;35(10):3976–94.
[19] Hvelplund F. Renewable energy and the need for local energy markets. Energy 2006;31(13):2293–302.
[20] Fracastoro GV, Nino E, Tommaso RMD. Influence of the boundary thermal conditions on the air change efficiency indexes. Indoor Air 1999;9:63–9.
[21] Bernal-Agustin JL, Fracastoro GV, Zubi G. High concentration photovoltaic systems applying III–V cells. Renew Sustain Energy Rev 20092645–52 (Elsevier).
[22] Acquaviva A, Aghemo C, Blaso L, Dalmasso D, Erba D, Fracastoro GV. Energy saving in existing buildings by an intelligent use of interoperable ICTs. Energy Effic 2013;6:707–23, http://dx.doi.org/10.1007/s12053-013-9211-0.
[23] Fracastoro GV, Mutani G, Perino M. Experimental and theoretical analysis of natural ventilation by windows opening. Energy Build 2002817–24(Elsevier).
[24] Xing, Y, Hewitt, N, Griffiths, P. Developing an integrated simulation model to design a 100% renewable building energy system. In: Proceedings of the international conference on future power and energy engineering. Shenzhen; 26–27 June, 2010. p. 46–9 http://dx.doi.org/10.1109/ICFPEE.2010.35.
[25] Jun, Z, Jie, W, Feng, LJ, Mei, GL, Min, L. An agent-based approach to renewable energy management in eco-building. In: Proceedings of the IEEE international conference on sustainable energy technologies. Singapore; 24–27 November 2008. p. 46–50 http://dx.doi.org/10.1109/ICSET.2008.4746970.
[26] Talbott J. Simply build green: a technical guide to the ecological houses at the Findhorn Foundation. Malta: Findhorn Press; 1997.
[27] Kasmai M. Climate and architecture. 8th ed. Tehran, Iran: Nashre khak; 2007.
[28] Leung, L Sky-sourced sustainability: How super tall building can benefit from height, Skidmore, Owings & Merrill LLP. Retrieved February 3, 2012 from ⟨http://www.som.com/resources/content/5/0/4/3/9/0/1/9/documents/SOM_Sky-SourcedSustainability.pdf⟩.
[29] Niknam, K 2012, Wind catcher, Available online, ⟨http://http://www.kniknam.com/fr?q=بادگیر&desturi.html⟩.
[30] Fracastoro GV, Serraino M. Energy analyses of buildings equipped with exhaust air heat pumps (EAHP). Energy Build 2010;42:1283–9 (Elsevier).
[31] Abrams E, Danielson EW, Levin J. Meteorology. 2nd ed.McGraw Hill; 2003.
[32] Landau LD, Lifshitz EM. Fluid mechanics. 2nd ed.Pergamon; 1979.
[33] Kittel C, Kroemer H. Thermal physics. 2nd ed.Freeman; 1980.
[34] PSAS. A. Quick Derivation relating altitude to air pressure. Portland State Aerospace Society. Retrieved from ⟨http://www.psas.pdx.edu⟩, 2004.
[35] URL9. 2012. Shelquist Engineering. Retrieved October 3, 2013, Available online, ⟨http://wahiduddin.net/calc/density_altitude.htm⟩.
[36] Sartipipour M. Renewable energies zoning towards the development of rural areas in Iran. Int J Acad Res 2011;3(2):771–7.
[37] Corgnati SP, Fracastoro GV, Nielsen PV, Perino M. Experimental and numerical analysis of air and radiant cooling systems in offices. Build Environ 2009;44:801–6.
[38] Leo Samuel DG, Maiya MP, Shiva Nagendra SM. Passive alternatives to mechanical air conditioning of building: a review. Build Environ 2013;66:54–64, http://dx.doi.org/10.1016/j.buildenv.2013.04.016.
[39] Research Center for Rural Architecture [RCRA]. Use of Renewable Energies in Rural Housing and Development. Tehran: Shahid Beheshti University Publication, 2009.
[40] Aber JD, Freuder R. Variation among solar radiation data sets for the Eastern US and its effects on predictions of forest production and water yield. Durham: Complex Systems Research Center, University of New Hampshire; 2000.